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Δ-production in $\bar{\rm p}$d-annihilation at rest *

Amand Faessler[1], A. Sibirtsev[2] and K. Tsushima[3] †

[1]Institut für Theoretische Physik, Universität Tübingen
Auf der Morgenstelle 14, D-72076 Tübingen, Germany

[2]Laboratory of Nuclear Problems, Joint Institute
of Nuclear Research, Dubna, 141980, Russia

[3]Department of Physics and Mathematical Physics
The University of Adelaide, Australia 5005

Abstract

We study the Δ-excitation in $\overline{p}d$ annihilation at rest. The invariant spectra of the π^+p and π^-p systems selecting the protons with momenta above 400 MeV/c are analyzed. The calculations reproduces reasonably the experimental data.

One of the traditional mechanisms of fast baryon production following the antiproton annihilation is the secondary interactions of the pions as well as the mesonic resonances in the nuclear environment. It is clear that an essential indication for the contribution of the meson rescattering is the excitation of the Δ-resonances.

The search for isobar was performed in $\overline{p}d$ annihilation by Kalogeropoulos et al. [1], but they found no Δ influence in πN-system. As was later shown by Voronov and Kolybasov [2] analyzing the reaction $\overline{p}d \to 2\pi^+3\pi^-p$ that the structure of the isobar may be significantly smeared out due to the contribution from πN-pairs in which the pion does not undergo rescattering. It was suggested that the Δ-resonance can be observed only when the recoil nucleons are selected with momenta above 200 MeV/c.

Recently the OBELIX collaboration from CERN measured the annihilation of stopped antiprotons in a deuteron target [3]. The invariant mass of protons with momenta larger than 400 MeV/c and π^+-mesons indicates a clean peak from Δ^{++}-resonances, whereas the Δ^0-resonance in the π^-p system was not found.

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Here we study the Δ-excitation in $\overline{p}d$ annihilation at rest. The annihilation amplitude from the statistical model and the πN amplitude from the resonance model were adopted in our calculations.

Similar to [4] we calculate the amplitude of the triangle diagram shown in fig.1 as

$$T = \frac{E_\pi + E_p}{2\pi(m - E_\pi)} \int \frac{T_1(\overline{p}N \to n\pi) T_2(\pi N)}{\mathbf{k}_1^2 - \mathbf{k}_2^2 + i\epsilon} \phi(\mathbf{k}_1 + \mathbf{Q}/2) d\mathbf{k}_1 \tag{1}$$

where T_1 is the amplitude of $\overline{p}N \to n\pi$ annihilation, E_π and E_p are the pion and the proton energies in the final state, $\mathbf{k}_1$ and $\mathbf{k}_2$ are the pion momenta before and after the interaction. Here m is the nucleon mass and $\mathbf{Q}$ is the deuteron momentum. The deuteron wave function $\phi(\mathbf{Q})$ for the Bonn potential [5] was adopted.

We use the annihilation probability from [6] as

$$|T_1(\overline{p}N \to n\pi)|^2 = G_f \frac{\lambda^{1/2}(s, m^2, m^2)}{2m^2} \frac{P_n}{I_n(s)} \tag{2}$$

where s is the squared invariant mass of $\overline{p}N$ system and λ is the Kälen function. Factor G_f stands for the charge configuration of the final system of n-pions and was calculated with the statistical approach as [7]

$$G_f = [n_+! n_-! n_0!]^{-1} \left[\sum_\beta (n_+! n_-! n_0!)_\beta^{-1} \right]^{-1} \tag{3}$$

where n_+, n_- and n_0 are the numbers of positive, negative and neutral π-mesons for a final charge system of $n = n_+ + n_- + n_0$ pions and the summation is performed over all reaction channels allowed for a given $n\pi$ system.

In eq.(2) the factor $I_n(s)$ accounts for the phase space volume of n-pions with invariant mass $\sqrt{s}$ and P_n stands for the probability for the creation of n-pions in $\overline{p}N$ annihilation, which was taken as [8]

$$P_n = (2\pi\sigma)^{1/2} exp \left[-\frac{(n-\nu)^2}{2\sigma} \right]$$
$$\nu = 2.65 + 1.78 lns, \quad \sigma = 0.174 \nu s^{0.2} \tag{4}$$

Accordingly to Hernandez et al. [6] the annihilation amplitude has a smooth momentum dependence and the momentum distribution of the pions are described by the n-body phase space.

The $T_2(\pi N)$ is the amplitude which accounts for the $\pi N \to \pi N$ scattering in the Δ-isobar region. This amplitude is calculated with the resonance model [9, 10]. The relevant interaction Lagrangian is given by,

$$\mathcal{L}_{\pi N \Delta} = \frac{g_{\pi N \Delta}}{m_\pi} \left(\bar{\Delta}^\mu \overrightarrow{\mathcal{I}} N \cdot \partial_\mu \vec{\phi} + \bar{N} \overrightarrow{\mathcal{I}}^\dagger \Delta^\mu \cdot \partial_\mu \vec{\phi} \right), \tag{5}$$

where $\vec{\mathcal{I}}$ is the isospin transition operator $\overrightarrow{\mathcal{I}}_{Mm} = \sum_{\ell=\pm1,0} (1\ell \frac{1}{2} m | \frac{3}{2} M) \hat{e^*}_\ell$, and $\vec{\phi}$ stands for the pion field. The coupling constant $g_{\pi N \Delta}$ appearing in the Lagrangian is determined by the experimental width Γ_Δ of the Δ resonance as,

$$\Gamma_\Delta = \frac{g_{\pi N \Delta}^2 F^2(\mathbf{q})}{12\pi} \frac{(\sqrt{m_N^2 + \mathbf{q}^{\,2}} + m_N)}{m_\Delta m_\pi^2} |\mathbf{q}|^3, \tag{6}$$

with $|\mathbf{q}| = \lambda^{\frac{1}{2}}(m_\Delta^2, m_N^2, m_\pi^2)/(2m_\Delta)$ and $F(\mathbf{q})$ being the form factor which simulates the finite size effects of the hadrons. This form factor is multiplied to each $\pi N\Delta$ vertex in the calculations, and explicit expression is,

$$F(\mathbf{q}) = \frac{\Lambda^2}{\Lambda^2 + \mathbf{q}^2}, \tag{7}$$

with Λ being the cut-off parameter. For the propagator $G_\Delta^{\mu\nu}$ of the Δ resonance, we use

$$iG_\Delta^{\mu\nu}(p) = i\frac{-P^{\mu\nu}(p)}{p^2 - m_\Delta^2 + im_\Delta\Gamma_\Delta}, \tag{8}$$

with

$$P^{\mu\nu}(p) = -(\gamma \cdot p + m_\Delta)\left[g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{1}{3m_\Delta}(\gamma^\mu p^\nu - \gamma^\nu p^\mu) - \frac{2}{3m_\Delta^2}p^\mu p^\nu\right]. \tag{9}$$

The cut-off parameter Λ appearing in the form factor $F(\mathbf{q})$ was fitted to the experimental total cross section for the $\pi^+ p$ interaction [11]. We get Λ=0.33 GeV, which corresponds to the value $g_{\pi N\Delta}^2/4\pi = 0.83$, by eq. (6) (without $F^2(\vec{q})$ in eq. (6) gives this value 0.38, that is comparable to the value of the Bonn potential [12] 0.35.).

Calculated spectra of the $\pi^+ p$ invariant mass from the reaction $\overline{p}d \to p\pi^+ 2\pi^- m\pi^0$ are shown in Fig.2. The experimental data were taken from [3]. Similar as in ref. [3] we select the protons with momenta above 400 MeV/c. The dashed line shows the Δ^{++}-resonance, whereas the dotted line shows the combinatorial background that comes from the pions which do not undergo interactions. The solid line is the sum and describes reasonably the experimental data. The isobar structure might be clearly reconstructed from the invariant mass distribution.

A quite different situation exists for the spectrum of the $\pi^- p$ invariant mass from the reaction $\overline{p}d \to p\pi^+ 2\pi^- m\pi^0$, which is shown in Fig.3. The signal from the Δ^0 resonance is to weak to be extracted from strong combinatorial background. In Fig.4 we show separate contributions from $\overline{p}d \to p\pi^+ 2\pi^- \pi^0$ (a) and $\overline{p}d \to p\pi^+ 2\pi^- 2\pi^0$ (b) reactions to the $\pi^- p$ invariant mass. Most promising is to study the Δ^0 excitation in the reaction $\overline{p}d \to p\pi^+ 2\pi^- \pi^0$, which shows narrow peak at the isobar region and large ratio of the Δ^0 amplitude to the combinatorial background at $M(\pi^- p) \simeq 1.25$ GeV.

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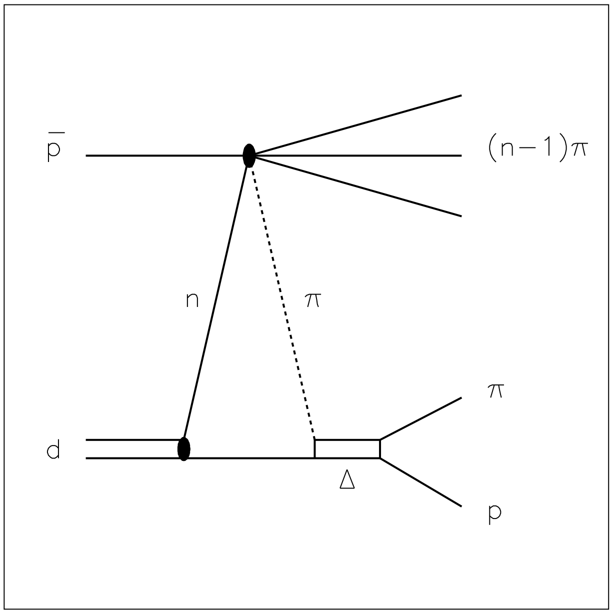

Figure 1: Pion rescattering diagram.

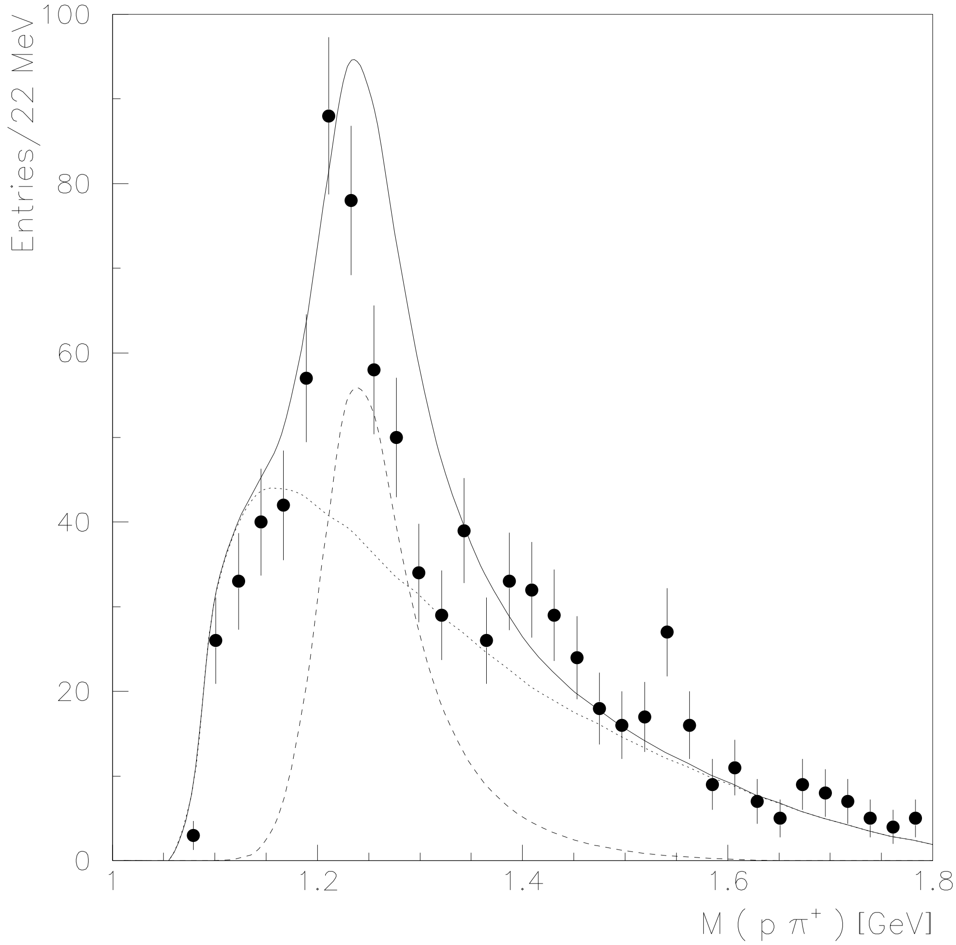

Figure 2: The spectrum of the π^+p invariant mass from the reaction $\overline{p}d \rightarrow p\pi^+2\pi^-m\pi^0$ for protons with momenta above 400 MeV/c. Experimental data are from [3] and lines show our results. Dashed line is the contribution from Δ^{++}-excitation, dotted from the combinatorial background, while the solid line shows the sum.

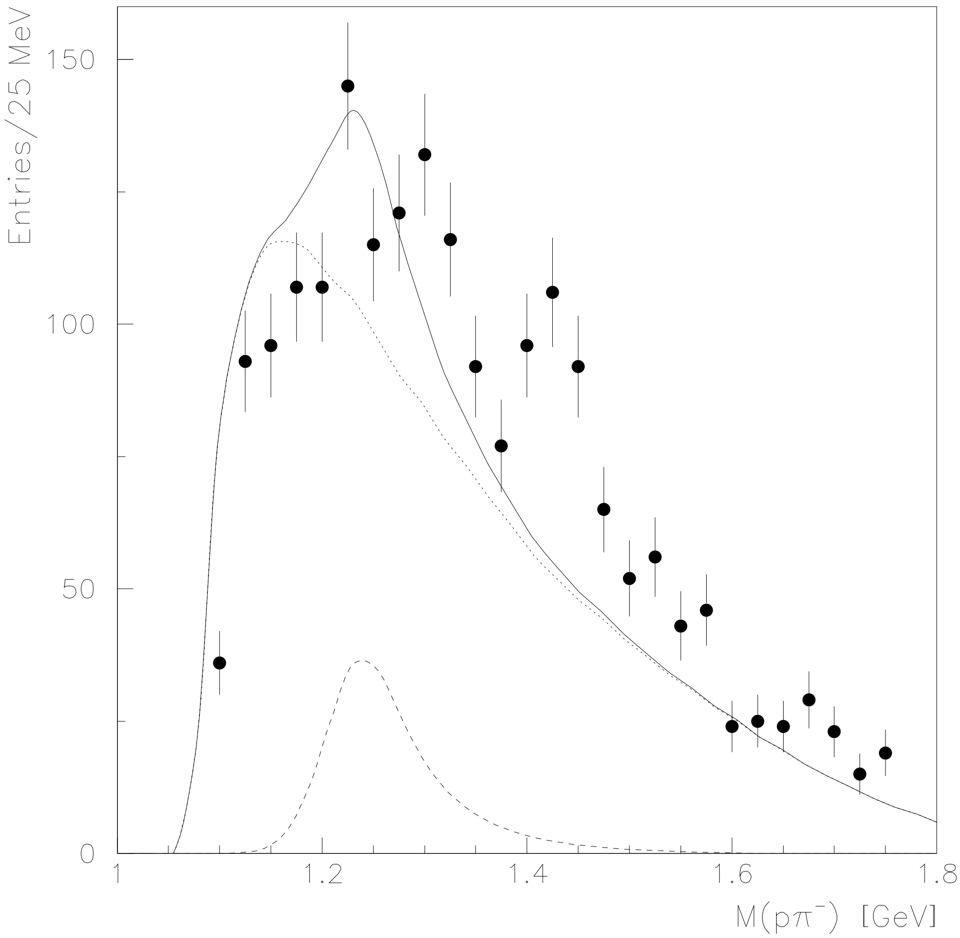

Figure 3: The spectrum of the $\pi^- p$ invariant mass from the reaction $\overline{p}d \rightarrow p\pi^+ 2\pi^- m\pi^0$ for protons with momenta above 400 MeV/c. Experimental data are from [3] and lines show our calculations. Dashed line is the contribution from Δ^0-excitation and dotted from the background. Solid line shows the sum.

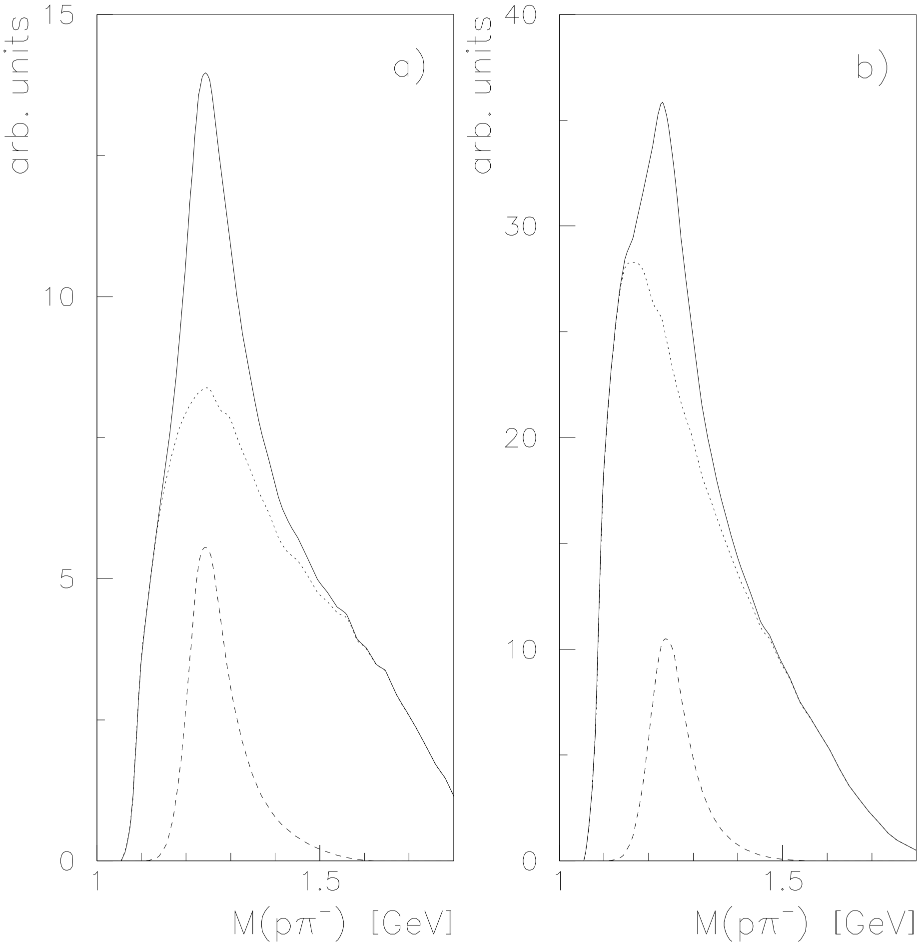

Figure 4: The spectra of the $\pi^- p$ invariant mass from the reactions $\overline{p}d \rightarrow p\pi^+ 2\pi^- \pi^0$ (a) and $\overline{p}d \rightarrow p\pi^+ 2\pi^- 2\pi^0$ (b) and for protons with momenta above 400 MeV/c. Dashed line is the contribution from Δ^0-excitation, dotted from the background and the solid shows the sum.